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Network Restoration and Recovery in Humanitarian Operations: Framework, Literature Review, and Research Directions

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Abstract

In the aftermath of large-scale events requiring humanitarian action, critical infrastructure networks in the affected areas, such as electrical power, transportation, telecommunications, water supply, and waste water networks, may be disrupted by the devastating impact of the event. In the short and long term following the event, activities to return these networks to the pre-disaster working state, which include debris clearance and disposal, infrastructure repair, network reconstruction, road repair and rehabilitation, and snow removal. The costly and complicated nature of these activities has led to an increased level of interest regarding this field in the OR/MS literature over the recent years. In this study, we present the results of a comprehensive overview of the literature on network restoration and recovery in humanitarian operations, and provide a framework to consider this body of literature. We classify the studies in terms of the problems addressed, main decisions, objectives, models, and solution methods for these problems. Based on ongoing work, we also underline potential directions for future research by pointing to the gaps between the needs in the field and the existing body of literature.

1 Introduction

Infrastructure networks play an important role in providing a lifeline for everyday activities of communities. Among these, road networks help businesses establish connectivity among various levels of the supply chains of their products and services, as well as facilitating the mobility of people and accessibility to critical facilities and resources in times of need. Similarly, power and telecommunication systems are crucial in supplying the energy and establishing connectivity among various entities of the community, whereas maintenance and cleanliness of water supply networks are important so as to maintain the health and well-being of the people using them.

In cases of events requiring humanitarian action, such as natural and human-inflicted disasters (e.g., earthquakes, hurricanes, floods, terrorist attacks) or long-term humanitarian issues (e.g., armed conflicts), restoration and recovery of infrastructure networks become increasingly important

due to mainly two reasons. In the short term, these networks provide the baseline for performing response activities such as evacuation, search-and-rescue, relief distribution, and establishing communication among the various stakeholders responding to the event. Hence, within the first few days or weeks following the event, the main goal is to bring these networks to at least minimal working conditions so that response activities can be performed. In the long term, the restoration and repair of infrastructure networks is an important factor in stabilizing the community and restoring at least some level of normalcy after the event. Consequently, timely recovery of these networks is of concern.

The recent trends in the occurrences of catastrophic events show that while the number of recorded events has increased (mainly due to better information systems, growth in global population and population density, and human-inflicted causes such as global warming), the number of casualties from such events is on the decline. For the period 1965-2015, the average annual number of deaths from disasters is around 100,000, whereas when the interval between 2000 and 2015 is considered, the death toll decreases to around 41,000 per year. On the other hand, an opposite effect is observed on the economic impacts of disasters; the estimated economic damages for these two periods are US\$ 11 billion and US\$ 30 billion per year, respectively [1]. The main reasons for the latter trend lie not only in the increase in population density and economic activity, but also in the increased investments in infrastructure networks, which generally incur substantial amounts of damage in cases of large-scale events.

Damages to infrastructure networks in the aftermath of large-scale catastrophic events can be in many different forms, including collapse of road networks and bridges, generation of debris, failure of power and telecommunication systems, damages on critical facilities, and build up of large amounts of snow. In any of these cases, the restoration and recovery activities are generally costly and complicated, and may significantly hamper the necessary response operations. For instance, Hurricane Katrina (2005) generated more than 100 million cubic yards of debris, the cleanup of which accounted for an estimated 27% of all disaster-related costs [2]. Similarly, Hurricane Sandy (2012) caused significant damage on the infrastructure systems, resulting in an estimated cost of US\$ 33 billion for repair and cleanup in the aftermath [3]. Following the Haiti earthquake (2010), despite the abundance of relief supplies, the damage in the road infrastructure resulted in transportation of these to people in need to be impossible [4]. The response activities to Typhoon Haiyan (2013) in the Philippines were severely exacerbated by the damage and debris on the road network; it took about six hours to make the 22 km journey from the airport to Tacloban City

center, which resulted in the loss of vital time for search-and-rescue activities [5]. Altogether, the experience from these events underlines the significance of the need for timely, efficient, and effective network restoration and recovery activities in the aftermath of large-scale events, so that both short-term and long-term needs for the infrastructure networks can be satisfied.

The increase in the number of and awareness for events requiring humanitarian action, as well as the importance of the effectiveness and efficiency of logistics (to which more than 80% of all disaster relief efforts can be attributed [6]) in determining the performance of humanitarian relief operations have led to substantial amount of research addressing humanitarian logistics in the last decade. Consequently, a number of survey papers have been published, which either present an overall view of the studies in this field or focus on a specific set of decisions. Among these, Altay and Green [7] present an extensive review on research in the OR/MS field regarding disasters until 2006. Apte [8] focuses on logistics decisions and discusses the unique characteristics and challenges of humanitarian supply chains. In Caunhye et al. [9], the emphasis is on the optimization models for emergency logistics, whereas de la Torre et al. [10] provide a review on disaster relief routing. Çelik et al. [11] take a broader perspective on humanitarian logistics in general, and classify the problems in this field based on the disaster life cycle addressed or the specific long-term humanitarian issue considered. Galindo and Batta [12] build upon Altay and Green [7] and update the findings in the latter study by reviewing the OR/MS papers regarding disaster management in the last decade. Anaya-Arenas et al. [13] provide a framework and a literature review on problems in relief distribution networks, whereas Faturechi and Miller-Hooks [14] discuss the performance assessment of transportation infrastructures in disasters, while providing an extensive literature review. Özdamar and Ertem [15] consider the models developed for the post-disaster stage and put additional emphasis on the information systems needs and applications in humanitarian logistics.

As also observed by Faturechi and Miller-Hooks [14], while there exists a vast body of literature in the performance assessment of infrastructure networks to cope with large-scale catastrophic events, the literature on the management strategies for these systems is more limited, but growing. In this paper, we aim to provide an extensive review on this growing field of literature, focusing on the restoration and recovery activities in the aftermath of large-scale catastrophic events.

The main contributions of this paper are three-fold. (1) To the best of our knowledge, this is the first paper that extensively reviews the recent literature on infrastructure network restoration and recovery in humanitarian operations. Thus, it also serves as a catalogue of research areas for those not familiar with this area of research. (2) It provides a framework for classifying the

body of literature in this field by analyzing the problem types, main decisions, objectives, modeling techniques and solution methods. (3) It underlines the potential gaps between theory and practice, and proposes further research directions based on ongoing work.

The remainder of this paper is organized as follows: Section 2 describes the scope of this paper, the search method, and the main findings of the literature search in detail. A classification of problem types, along with decisions, objectives, models, and solution methods is presented in Section 3. Section 4 describes a number of potential further research directions and concludes the paper.

2 Scope of the Study, Search Method, and Main Findings

As evidenced by the number of review papers that were described in Section 1, a vast amount of studies have been carried out on decision making in humanitarian operations. Thus, we begin this section by defining the scope of our study in order to specify the criteria for papers in this area to be included. This is followed by the systematic search procedure applied to determine the list of papers to review. We also discuss the main findings of our review, such as the number of studies over 5-year intervals, number of publications by journal, and the number of common papers with the aforementioned reviews in Section 1.

2.1 Scope of the Study

The main emphasis of our work is on network restoration and recovery, for which the practical applications lie in the field of humanitarian logistics. Borrowing from Çelik et al. [11], we define humanitarian logistics as the set of “logistics activities related to preventing, reducing, preparing for, responding to, or recovering from human suffering and environmental and financial effects due to a disaster or a long-term humanitarian issue.” Key to this definition are the terms “disaster” and “long-term humanitarian issue,” both of which are included within the scope of this paper. As in Galindo and Batta [12], we define a disaster as “a shocking event that seriously disrupts the functioning of a community or society, by causing human, material, economic or environmental damage that cannot be handled by local agencies through standard procedures.” Using the definition in Çelik et al. [11], we differentiate between disasters and long-term humanitarian issue in that the cause of the latter cannot be traced back to a specific event. Hence, examples of disasters in this scope include earthquakes and hurricanes, whereas examples of long term humanitarian issues

include food security and the HIV pandemic.

The main focus of this paper being network restoration and recovery implies that humanitarian logistics problems (e.g., relief distribution, evacuation planning, inventory prepositioning, etc.) without any regard to these two aspects are left out of the scope of this paper. In addition, to avoid significant overlaps with Fatuerechi and Miller-Hooks [14], studies measuring the resilience of an infrastructure network (e.g., in terms of risk, vulnerability, reliability, etc.) are not considered. The literature review is also limited to quantitative and prescriptive decision making models. Consequently, descriptive studies, qualitative analyses, and case studies without any quantitative decision making aspects are also outside the scope of this paper.

2.2 Systematic Search Method

Upon having defined the objectives and scope of the study, a systematic search was performed on a set of databases that were frequently used in prior literature reviews, which included ISI's Web of Science, Business Source Complete, Compendex, Engineering Village 2, Scirus, Scopus, Jstor, and Sci-tation. In the original search, two main set of keywords were used: (1) at least one of "disaster*," "catastroph*," "humanitarian," "emergenc*," "logistic*," or "extreme event*," and (2) at least one of "debris clearance," "debris removal," "road restoration," "accessibility," "infrastructure repair," "network repair," "network *construction," "emergency repair," "network recover*," "network restor*," "emergency restor*," "snow remov*," or "link restor*." To avoid searching through studies in areas not directly relevant to this study, study areas such as social sciences, biology, geophysics, etc. were filtered out. On the other hand, studies in relevant fields such as electrical or civil engineering for which the techniques and methods of OR/MS were applied were particularly included. Among the papers that satisfy the criteria, three types of papers were mainly included: (i) those that directly address decisions in humanitarian operations, (ii) those that do not necessarily focus on humanitarian operations, but include it as one of the potential application areas of the presented work, and (iii) papers that do not consider humanitarian operations as an application area, but the work can be directly applied to such operations.

The year range for the search was set between 2000 and 2016, due mainly to two reasons. First, the structuring and formalization of the management of humanitarian operations is quite recent and hence, a vast majority of OR/MS studies in this area are after the turn of the century [13]. Second, earlier studies in this area are well-covered in the earlier reviews on OR/MS studies in disaster management and humanitarian logistics. The possibility of missing relevant studies due to

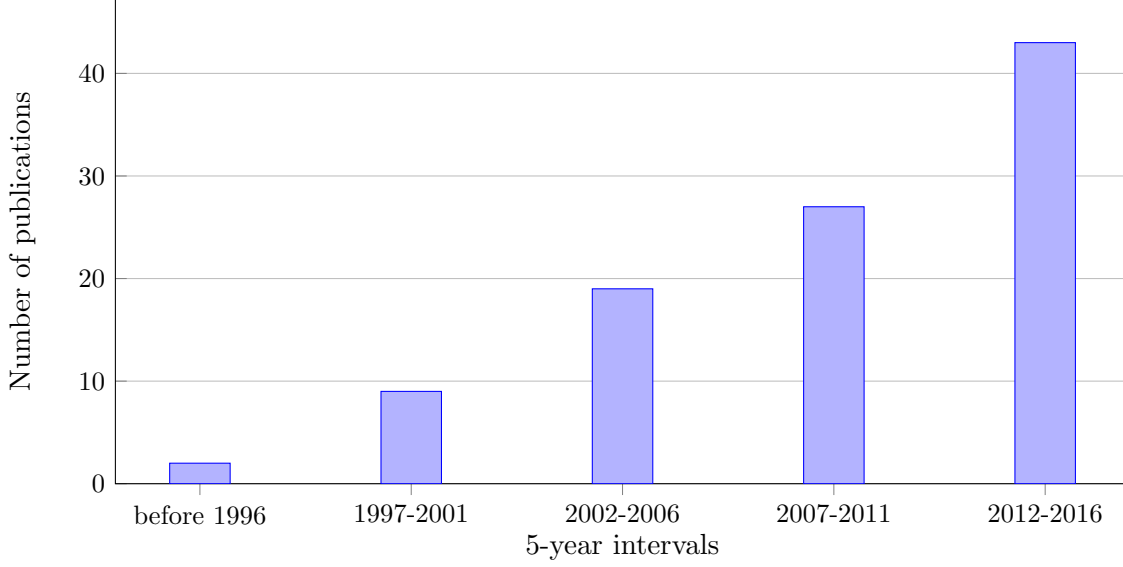


Figure 1: Number of studies for each 5-year interval

the limits set by the aforementioned criteria was aimed to be avoided by thoroughly analyzing the references within each relevant paper and the studies that cite each relevant paper.

2.3 General Findings from the Review

The systematic search procedure resulted in 100 papers, which were finalized after further manual processing. This set of studies includes 87 journal papers, 3 book chapters, 7 conference proceedings, 2 working papers, and 1 unpublished thesis.

2.3.1 Trends over time

To analyze the number of network restoration and recovery studies over time, Figure 1 shows the number of papers for five-year intervals. The earliest study included in the review is in 1994, with a total of six papers before 2000. As expected, the trend for the studies on network restoration and recovery in humanitarian operations follows that for the studies on humanitarian operations in general, and thus there is a substantial increase in the number of published papers; from a total of nine papers in 1997-2001 to a total of 43 papers in 2012-2016.

2.3.2 Distribution by journal

Figure 2 displays the number of studies included in our review by journal for journals that have at least two studies reviewed in this paper. Among these, European Journal of Operational Re-

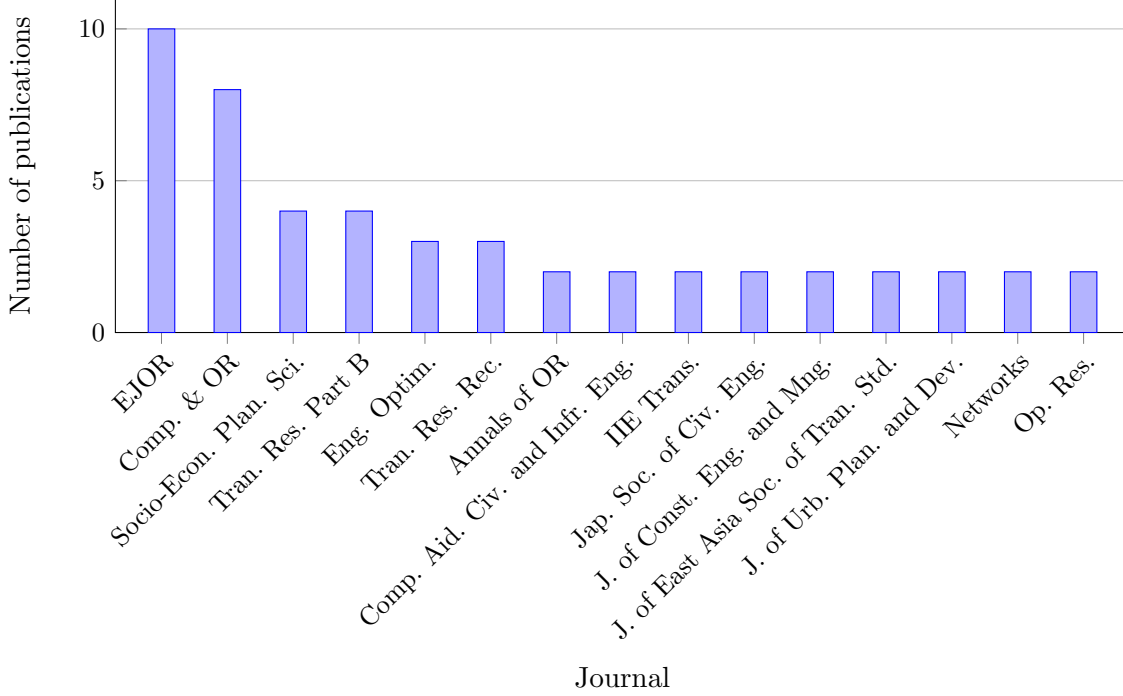


Figure 2: Number of studies by journal (for journals that have at least two publications reviewed in this paper)

search (EJOR) appears at the top, as is the case in [7]. Following EJOR are also journals in the OR/MS field, namely Computers & Operations Research, Socio-Economic Planning Sciences, and Transportation Research Part B. An interesting observation here is that Journal of the Operational Research Society, which appears as one of the top two journals in this ranking in both Altay and Green [7] and Galindo and Batta [12], is not represented by any study in this review. Also included in Figure 2 are journals from the Civil Engineering field, such as Computer-Aided Civil and Infrastructural Engineering, Japan Society of Civil Engineering, and Journal of Construction Engineering, as well as a journal from the Urban Planning field, namely Journal of Urban Planning and Development. The remaining 50 studies not included in Figure 2 are all published in distinct journals, books, or conference proceedings, which shows the variety of sources in which the studies on network restoration and recovery are published.

2.3.3 Overlaps with existing literature reviews

Given the abundance of review papers in the area of humanitarian operations, the overlaps between our work and the aforementioned review papers in Section 1 may be of interest. For this end, Figure 3 presents the number of common papers between our work and each of the review papers discussed

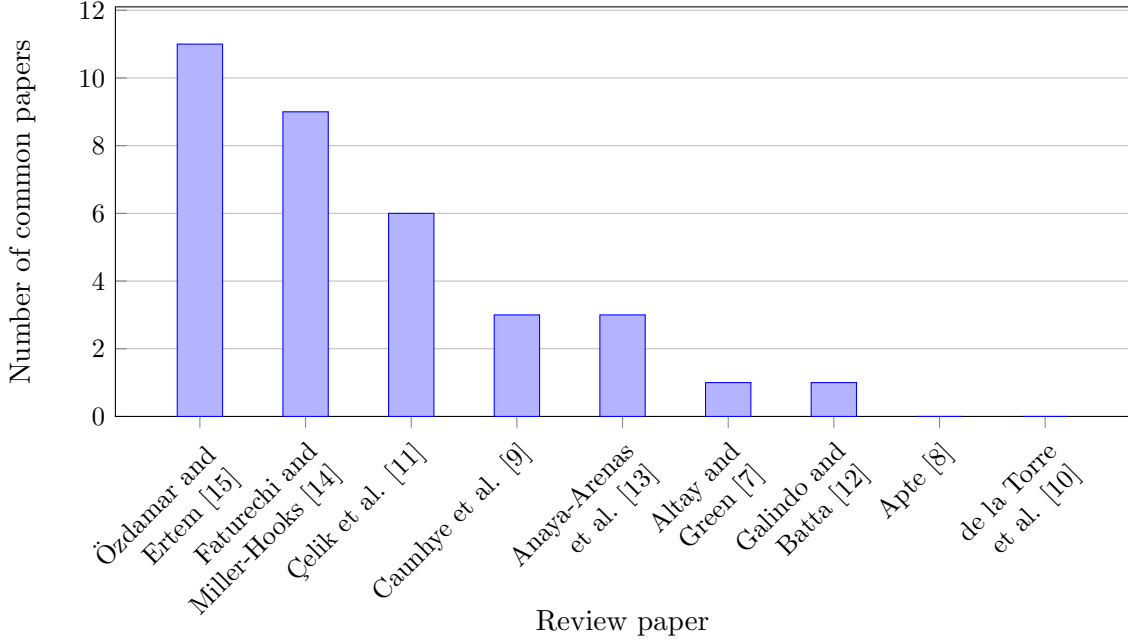


Figure 3: Number of common papers between our work with each of the review papers in the humanitarian operations area

in Section 1. As the figure also shows, Özdamar and Ertem [15], Faturechi and Miller-Hooks [14], and Çelik et al. [11] have the highest number of common papers with our work (11, 9, and 6 common papers, respectively). For the first two, one of the main reasons for this is the recentness of these reviews. Additionally, all three papers review similar areas in humanitarian operations; Özdamar and Ertem [15] consider post-disaster humanitarian operations, Faturechi and Miller-Hooks [14] focus on the assessment of transportation infrastructure performance in disasters, and Çelik et al. [11] review the humanitarian logistics area in general. Nevertheless, 79 of the 100 papers reviewed in this paper do not appear in any of the nine review papers given in Figure 3, which leads us to safely conclude on the uniqueness of most of the papers in this review.

2.3.4 Main objectives

The extent of efficiency and effectiveness at which the network restoration and recovery activities are performed can be measured in a variety of ways. In humanitarian operations, the main focus on prioritizing the beneficiaries' needs usually leads to defining the main objectives in terms of the beneficiaries' standpoint as well. Within the context of network restoration and recovery, such measures include completion time of the activities, utilities or benefits from satisfying the beneficiaries' demand (or penalties from unsatisfied demand), measures of accessibility of beneficiaries to critical

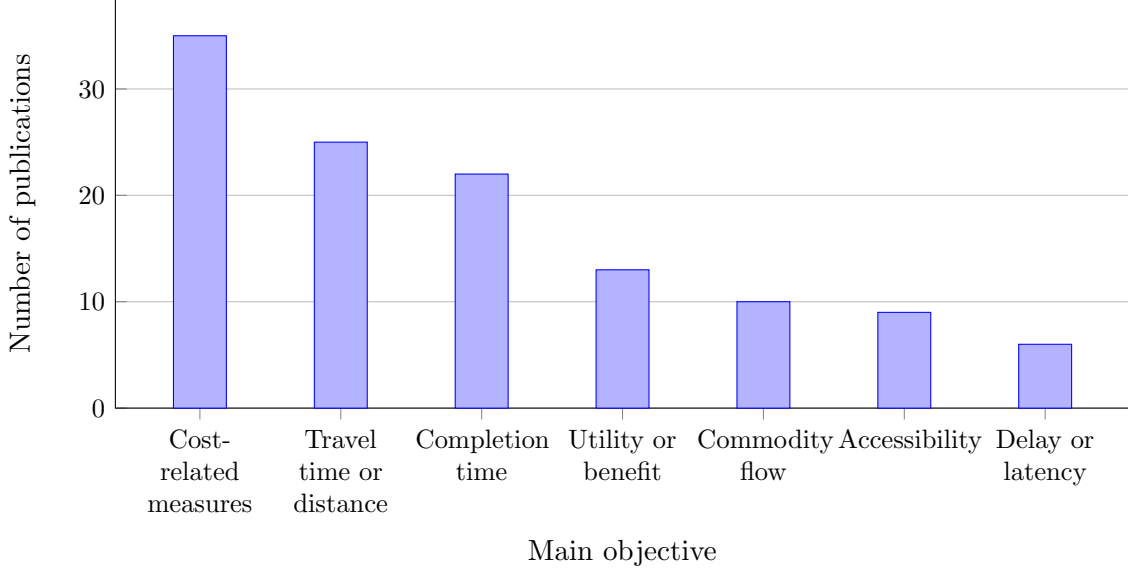


Figure 4: Number of studies by main objective

facilities or supply points, and amount of flow of people or commodities that can be handled by the network after restoration or recovery is complete. In addition to these, economic measures such as cost-related objectives, or efficiency-based measures such as travel time or distance of the crews may also be used.

A summary of the objectives used in the studies are presented in Figure 4. An interesting observation from the figure is that despite the humanitarian nature of the decision-making environment, efficiency-based measures are more inherent in the papers reviewed. A total of 35 papers use cost-related measures as the main objective, whereas a further 25 aim to minimize the travel time or distance of the restoration or repair crews/vehicles. Among the beneficiary-oriented objectives, timely completion of the operations is the most highly-used objective, followed by maximizing the utility or benefit from satisfying the beneficiaries' demand. A detailed assessment of these objectives by problem type is made in Section 3.

An important aspect in providing humanitarian commodities or services to beneficiaries is the *equity* of distribution. While the definition of equity is context-dependent, two classes based on different theories of justice are generally prevalent: (1) *Aristotelian* (proportional) equity, where the aim is to allocate resources in proportion to the beneficiaries' needs [28], and (2) *Rawlsian* (maximin) equity or difference principle, where the main aim is to maximize the well-being of the worst-off beneficiaries [29].

A total of 12 papers in our review use equity-based measures as the main objective, which have

Table 1: Equity-based objectives in network restoration and recovery

Reference	Equity-based objective
Meng and Yang [16]	Ratio of travel cost before and after the enhancement needs to be within a certain threshold for all users
Liberatore et al. [17]	All distribution times must be below a target threshold
Chen and Yang [18]	The ratio of travel time after implementation over that before implementation is below a certain threshold for all O-D pairs
Feng and Wu [19]	Minimize the standard deviation of the intraregional and interregional differences in average travel speed from every main city to the regional center
Lagaros and Karlaftis [20]	Minimize variance in inspection times between districts
Kallioras et al. [21]	Minimize variance in inspection times between districts
Feng and Zhang [22]	Gini coefficient, Theil index, mean log deviation, relative mean deviation, coefficient of variation, Atkinson index
Yan and Shih [23]	Minimize maximum repair completion time over all nodes
Campbell and Lowe [24]	Minimize the maximum-length shortest path between any pair of nodes
Averbakh and Pereira [25]	Minimize maximum lateness of vertices or number of tardy vertices
Antunes et al. [26]	Maximize aggregate weighted accessibility for $(1 - \epsilon)100\%$ of demand points where accessibility gains are smaller
Ranskiarbum and Mason [27]	Maximize minimum percent satisfied demand

been summarized in Table 1. Here, Aristotelian measures of equity generally focus on bounding the ratio of the travel cost or time before or after the restoration of the network within a certain threshold. Rawlsian equity measures aim to minimize the variance (or standard deviation) of differences; minimize the maximum time or cost incurred; or maximize the minimum unsatisfied percent demand among the beneficiaries.

2.3.5 Solution methods

The solution methods used to solve the models addressing network restoration and recovery decisions are given in Figure 5. Among these, exact and metaheuristic methods are the most widely used ones, being used in 37 and 36 of the papers reviewed, respectively. A further 28 papers apply heuristic methods. Approximation methods are also used, albeit not very frequently, and mostly for theoretical purposes. A limited number of simulation models are also developed to evaluate a set of discrete decisions. These methods will be analyzed in more detail by problem type in Section 3.

Whereas heuristics, approximation methods, and simulation models are more problem-specific and cannot be classified any further, exact models and metaheuristic models used in the reviewed

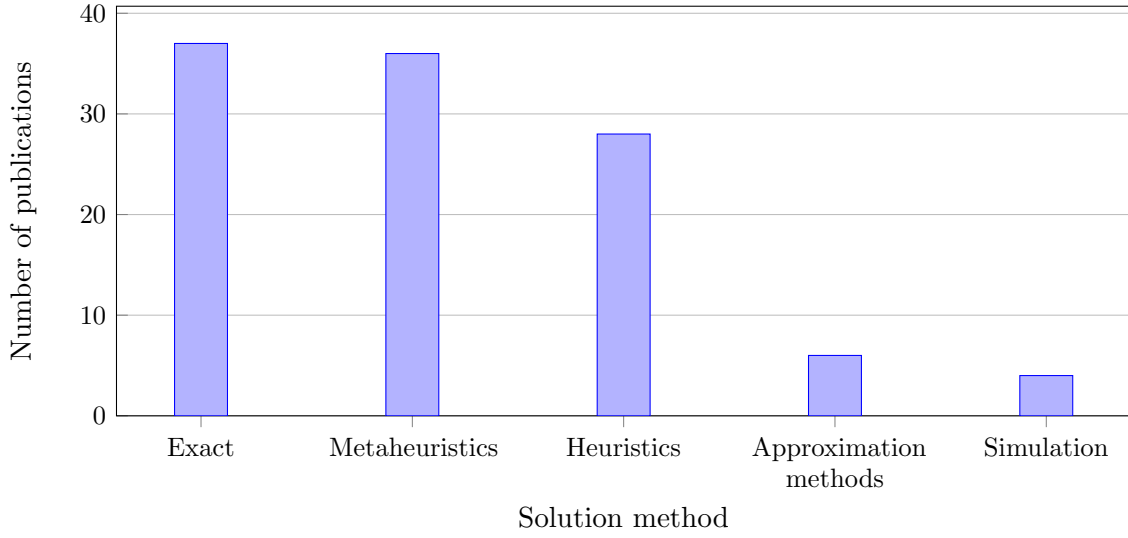


Figure 5: Number of studies by solution method

Table 2: Exact solution methods for network restoration and recovery

Method	References
Mixed integer programming	Krumke et al. [30], Balakrishnan et al. [31], Chien [32], Lee et al. [33, 34], Murawski and Church [35], Fu et al. [36], Matisziw et al. [37], Fetter and Rakes [38], Averbakh and Pereira [25, 39], Hu and Sheu [40], Torabi et al. [41], Baxter et al. [42], Asaly and Salman [43], Alvarez et al. [44], Sharkey et al. [45], Kalinowski et al. [46], Lorca et al. [47], Ye and Ukkusuri [48], Ransikarbum and Mason [27], Akbari and Salman [49]
Bilevel programming	Meng and Yang [16], Gao et al. [50]
Inverse optimization	Wang and Hu [51, 52]
Constraint programming	Gong et al. [53], Coffrin et al. [54]
Dynamic programming	Guha et al. [55], Kiyota et al. [56], Maya-Duque et al. [57]
Partially observable Markov decision processes	Çelik et al. [58]
Stochastic programming	Chen and Yang [18], Ukkusuri and Patil [59], Coffrin et al. [54], Peeta et al. [60]
Polynomial-time algorithms	Campbell and Lowe [24], Averbakh [39]

Table 3: Metaheuristic methods for network restoration and recovery

Method	References
Genetic algorithm	Tamura et al. [61], Sato and Ichii [62], Chen and Tzeng [63], Chen and Zheng [64], Hegazy et al. [65], Chen and Yang [18], Karlaftis et al. [66], Lee and Kim [67], Xu et al. [68], Furuta et al. [69], Kim et al. [70], Orabi et al. [71, 72], Santos et al. [73], Chen et al. [74], Xie et al. [75], Feng and Zhang [22], Onan et al. [76]
Simulated annealing	Chen and Zheng [64], Meng and Yang [16], Antunes et al. [26], Kim et al. [70], Wang and Chang [77],
Tabu search	Pramudita and Taniguchi [78]
Greedy randomized adaptive search	Scaparra and Church [79], Maya-Duque and Sörensen [80], Maya-Duque et al. [57]
Memetic algorithm	Handa et al. [81, 82]
Large-scale neighborhood search	Maya-Duque and Sörensen [80], Salazar-Aguilar et al. [83], Maya-Duque et al. [84], Quirion-Blais et al. [85]
Ant colony optimization	Yan and Shih [23], Yan et al. [86]
Harmony search	Kallioras et al. [21]

papers can be further classified. In Table 2, exact solution methods are classified under the modeling techniques used by specific papers. As Table 2 also shows, majority of the papers applying exact methods employ mixed integer models, which generally is the case in the exact solution of network optimization models in general. Other exact methods used to solve deterministic problems include bilevel programming, inverse optimization, constraint programming, and algorithmic approaches, although the usage of the latter is limited. For models involving uncertainty, dynamic programming and stochastic programming are used by three papers each, whereas partially observable Markov decision processes are employed by one paper. Another important conclusion from Table 2 is the disparity between deterministic and stochastic problems that can be exactly solved, which can be attributed to the inherent difficulty of solving stochastic models to optimality.

A similar classification of metaheuristic methods is given in Table 3. A vast majority of the papers employing metaheuristics use genetic algorithms, followed by simulated annealing, used by five papers. Neighborhood search approaches such as greedy randomized adaptive search (GRASP) and large-scale neighborhood search (VNS) are being more frequently used in recent papers.

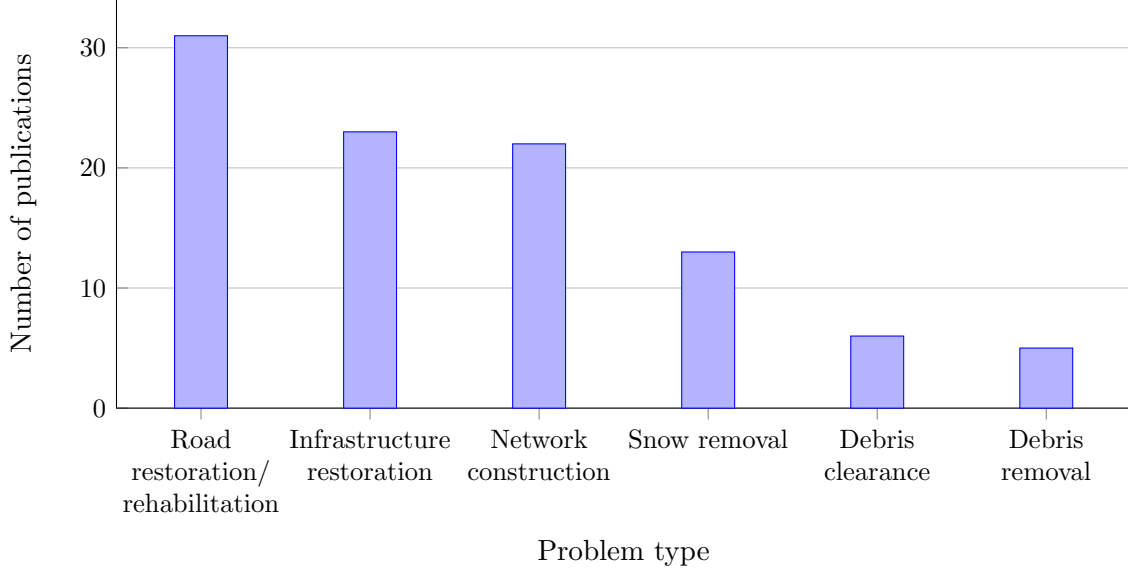


Figure 6: Number of studies by problem type

3 A Classification of Decision Problems in Network Restoration and Recovery in Humanitarian Operations

In this section, we provide a framework to classify the decision-making problems in network restoration and recovery in humanitarian operations. In doing so, we classify the set of decisions, objectives, and solution methods, while summarizing the body of literature for each problem type.

A summary of the problem types and the number of papers corresponding to each within the review are provided in Figure 6. Based on the findings summarized in this figure, we classify the problems faced in network restoration and recovery into six main groups. Road restoration and rehabilitation, which is the most widely studied problem type (31 out of 100 papers), involves either restoration of the transportation infrastructure into its pre-event state, or the improvement or strengthening of the network so that increased flow of people can be handled. Similarly, infrastructure restoration problems consider the restoration of other types of networks, such as power and telecommunications networks. Network construction problems focus on the addition of new nodes or edges to an existing network, so that capacity and accessibility can be increased. Snow removal problems involve the salting and plowing of large amounts of snow in the aftermath of large scale snowfall or avalanches. Debris clearance consists of opening up debris-covered roads by pushing the debris to road sides, whereas debris removal aims to collect, transport, and dispose or recycle the debris in special temporary facilities. While debris clearance may be considered a special ap-

plication of the road rehabilitation/restoration problems, we treat this as a separate problem due to the requirement of physical connectivity in determining which roads to clear of debris at any decision epoch.

In describing each problem type, we refer to Tables 4 and 5, which classify the solution methods and objectives for each problem type, respectively. The main decisions in each problem type are also provided in separate tables, given in Tables 6 through 11.

3.1 Debris Clearance

Management of debris generated by large-scale disasters is one of the costliest and most complicated aspects of disaster management. As also pointed out by FEMA [2], debris is detrimental in the short term, as it covers up roads and hampers search-and-rescue activities, accessibility to critical facilities, and relief distribution; whereas in the long-term it poses threats to human health and environment. Another important aspect regarding debris management is that the amount of debris generated is usually equivalent to years of solid waste that would be otherwise generated by the community, which implies that disposal of such amounts of debris might take substantial amounts of time.

The increased importance of debris management has led to the preparation of local and federal guidelines in the United States and throughout the world (e.g., [2], [114], [115]). However, quantitative decision making models regarding debris management are quite recent and still developing.

In the immediate few days following the disaster, debris clearance activities are aimed at pushing the resulting debris to road sides so that relief distribution, search-and-rescue, and access to critical facilities can be maintained. The existing body of literature on debris clearance is quite recent and limited. Among these, Özdamar et al. [87] determine the assignments and routes of clearance crews to minimize the makespan and maximize the accessibility of each node to other nodes throughout the network over multiple periods. Pramudita and Taniguchi [78] further incorporate determination of temporary facility locations and develop a tabu search approach to minimize total cost. Stilp et al. [88] consider a multi-period problem and aim to minimize the penalty due to unsatisfied relief demand, which is solved by means of heuristics. Çelik et al. [58] extend this problem to involve stochasticity in clearance resource requirements, and use a partially observable Markov decision process model and heuristics. Şahin et al. [89] and Berktaş et al. [90] solve routing problems by means of heuristics to minimize the total travel and clearance times of the crews.

Table 4: Classification of studies by problem type and solution method

Problem Type	Methods			
	Exact	Approximation	Heuristic	Metaheuristic
Debris clearance	Çelik et al. [58]		Özdamar et al. [87], Çelik et al. [58], Stulp et al. [88], Şahin et al. [89], Berktaş et al. [90]	Pramudita and Taniguchi [78]
Debris collection and disposal	Fetter and Rakes [38], Hu and Sheu [40], Lorea et al. [47]		Askarizadeh et al. [91]	Onan et al. [76]
Infrastructure restoration	Guha et al. [55], Balakrishnan et al. [31], Chien [32], Lee et al. [34, 67], Gong et al. [53], Matisziw et al. [37], Coffrin et al. [54], Sharkey et al. [45]	Guha et al. [55], Balakrishnan et al. [92]	Balakrishnan et al. [92], Wang et al. [93], Nurre et al. [94], Çavdaroglu et al. [95], Nurre and Sharkey [96]	Sato and Ichii [62], Fiedrich et al. [97], Hegazy et al. [65], Lee and Kim [33], Xu et al. [68], Furuta et al. [69]
Network construction	Krumke et al. [30], Meng and Yang [16], Chen and Yang [18], Gao et al. [50], Campbell and Lowe [24], Murawski and Church [35], Ukkusuri and Patil [59], Peeta et al. [60], Averbakh [39], Averbakh and Pereira [25, 101], Baxter et al. [42], Kalinowski et al. [46]	Krumke et al. [30], Baxter et al. [42], Kalinowski et al. [46], Engel et al. [102]	Krumke et al. [30], Antunes et al. [26], Campbell and Lowe [24], Pourmohammadi [103], Peeta et al. [60], Maya-Duque et al. [84], Baxter et al. [42], Averbakh and Pereira [25], Kalinowski et al. [46]	Meng and Yang [16], Antunes et al. [26], Chen and Yang [18], Scaparra and Church [79], Kim et al. [70], Santos et al. [73], Maya-Duque et al. [84], Feng and Zhang [22]
Road restoration/rehabilitation	Kiyota et al. [56], Wang and Hu [51], Torabi et al. [41], Aksu and Özdamar [104], Asaly and Salman [43], Alvarez et al. [44], Ye and Ukkusuri [48], Maya-Duque et al. [57], Ransikarbum and Mason [27], Akbari and Salman [49]	Bonyuet et al. [105], Yan and Shih [106], Yan et al. [107, 108], Aksu and Özdamar [104], Liberatore et al. [17], Akbari and Salman [49]	Bonyuet et al. [105], Yan and Shih [106], Yan et al. [107, 108], Aksu and Özdamar [104], Liberatore et al. [17], Akbari and Salman [49]	Tamura et al. [61], Chen and Tzeng [63], Chen and Zheng [64], Karlaftis et al. [66], Orabi et al. [71, 72], Chen et al. [18], Maya-Duque and Sörensen [80], Lagaros and Karlaftis [20], Yan and Shih [23], Wang and Chang [77], Kallioras et al. [21], Maya-Duque et al. [57]
Snow removal	Fu et al. [36]		Haghani and Qiao [109], Perrier et al. [110], Jang et al. [111]	Handa et al. [81, 82], Salazar-Aguilar et al. [83], Xie et al. [75], Quirion-Blaiz et al. [85]

Table 5: Classification of studies by problem type and objective

Objectives							
Problem Type	Delay/latency	Travel time/distance	Completion time	Accessibility	Utility/benefit	Cost	Flow
Debris clearance		Şahin et al. [89], Berktaş et al. [90]	Özdamar et al. [87], Şahin et al. [89], Berktaş et al. [90]	Özdamar et al. [87]	Çelik et al. [58], Stilp et al. [88]	Pramudita and Taniguchi [78]	
		Onan et al. [76], Askarizadeh et al. [91]	Lorca et al. [47]			Fetter and Rakes [38], Hu and Sheu [40], Lorca et al. [47], Onan et al. [76]	
Debris collection and disposal						Balakrishnan et al. [31, 92], Hegazy et al. [65], Wang et al. [93], Lee and Kim [33], Lee et al. [34, 67], Gong et al. [53], Matisziw et al. [37], Çavdaroglu et al. [95], Nurre and Sharkey [96], Gonzalez et al. [100]	
							Matisziw et al. [37], Nurre et al. [94], Nurre and Sharkey [96], Sharkey et al. [45]
Infrastructure restoration	Guha et al. [55], Chien [32], Xu et al. [68], Gong et al. [53], Sharkey et al. [45]	Gong et al. [53], Çavdaroglu et al. [95]	Lee and Kim [33], Furuta et al. [69], Gong et al. [53]		Guha et al. [55]		
Network construction		Scaparra and Church [79], Gao et al. [50], Campbell and Lowe [24], Kim et al. [70], Pourmohammadi [103], Feng and Zhang [22]	Averbakh [39], Averbakh and Pereira [25, 101]	Antunes et al. [26], Feng and Wu [19], Murawski and Church [35], Peeta et al. [60], Santos et al. [73]	Meng and Yang [16], Chen and Yang [18], Ukkusuri and Patil [59]	Gao et al. [50], Maya-Duque et al. [84], Feng and Zhang [22], Baxter et al. [42]	Scaparra and Church [79], Kim et al. [70], Pourmohammadi [103], Kalinowski et al. [46]
	Krumke et al. [30]						
Road restoration/rehabilitation		Chen and Tzeng [63], Chen and Zheng [64], Yan and Shih [106], Chen et al. [74], Maya-Duque and Sørensen [80], L'Agaros and Karlaftis [20], Kallioras et al. [21], Asaly and Salman [43], Liberatore et al. [17], Alvarez et al. [44]	Chen and Tzeng [63], Chen and Zheng [64], Yan and Shih [23, 106], Orabi et al. [72], Aksu and Özdamar [104], Yan et al. [86], Kallioras et al. [21], Akbari and Salman [49]	Feng and Wang [112], Asaly and Salman [43]	Kiyota et al. [56], Karlaftis et al. [66], Orabi et al. [71], Chen et al. [74], Ye and Ukkusuri [48], Maya-Duque et al. [57], Ransikarbun and Mason [27]	Cho et al. [113], Bonyuet et al. [105], Wang and Hu [51, 52], Karlaftis et al. [66], Orabi et al. [71, 72], Yan et al. [86, 107], Wang and Chang [77], Torabi et al. [41]	Chen and Zheng [64], Liberatore et al. [17]
Snow removal		Haghani and Qiao [109], Xie et al. [75], Quirion-Blais et al. [85]	Perrier et al. [110], Jang et al. [111], Quirion-Blais [85]		Fu et al. [36]	Handa et al. [81, 82], Fu et al. [36]	

Table 6: Main decisions in debris clearance

References	Decisions				
	Clearance sequencing	Crew assignment	Routing	Commodity flow	Depot location
Özdamar et al. [87]	X	X	X		
Pramudita and Taniguchi [78]			X		X
Çelik et al. [58], Stulp et al. [88]	X			X	
Şahin et al. [89], Berktaş et al. [90]			X		

Table 7: Main decisions in debris collection and disposal

References	Decisions		
	Facility location	Process selection	Capacity decisions
Fetter and Rakes [38], Lorca et al. [47]	X	X	X
Hu and Sheu [40]		X	
Onan et al. [76], Askarizadeh et al. [91]	X		

Table 8: Main decisions in infrastructure restoration

References	Decisions				
	Repair scheduling	Flow decisions	Resource allocation	Facility location	Selection of components to repair
Sato and Ichii [62], Balakrishnan et al. [31, 92], Chien [32]	X	X		X	
Guha et al. [55], Friedrich et al. [97], Çagnan et al. [98], Çagnan and Davidson [99], Gong et al. [53]			X		
Wang et al. [93]		X		X	
Lee and Kim [67], Gonzalez et al. [100]					X
Lee et al. [33, 34], Nurre et al. [94], Çavdaroglu et al. [95], Sharkey et al. [45]	X	X	X		X
Xu et al. [68], Matisziw et al. [37]	X				
Coffrin et al. [54], Nurre and Sharkey [96]		X	X		

3.2 Debris Collection and Disposal

As given in Table 7, the main decisions in debris collection and disposal may involve location of temporary processing facilities, selection of processes to employ in these facilities, possibly along with capacities, and the flow of debris from the location it is generated to the final dumping site.

A recent consideration throughout the debris collection and disposal operations is the possibility of recycling the debris. The need for recycling has become evident in large-scale disasters where space to dispose of the debris is scarce, such as the Haiti earthquake (2010) and the cascading disasters in Japan (2011). Furthermore, a recent program by FEMA offers incentives to local communities that recycle and reuse disaster debris, further motivating the need for developing models for these decisions [38].

Similar to debris clearance, the body of literature on quantitative decision models for debris collection and disposal is scarce. Fetter and Rakes [38] develop a MIP model to address the decisions of processing site location, process availability, and debris flow with the aim of minimizing system-wide costs. Lorca et al. [47] further extend this study by involving more precise decisions such as sorting during collection. Hu and Sheu [40] consider the additional psychological cost on the population due to long-term effects of the debris and aim to make decisions on process selection and debris flow by means of an exact MIP model. Onan et al. [76] develop a two-stage model with multiple objectives so as to minimize the population exposed to debris and the system-wide costs. Askarizadeh et al. [91] make facility location and debris-facility assignment decisions by means of GIS-based decision support tools so that total transportation time is minimized.

An interesting observation from debris collection and disposal problems is that the size and nature of these problems tend to enable exact solutions to be more easily found than in debris clearance problems, as also evidenced in Table 4.

End users of quantitative decision models in humanitarian operations generally require the use of user-friendly decision support tools, as they may not be technically knowledgeable on the models and solution approaches. Lack of such tools generally result in an important gap between theory and practice in this field, which happens to be the case for the papers reviewed in this study as well. In considering the allocation of road segments to debris collection contractors, Stilp et al. [116] build such a user-friendly tool to implement the models proposed in their study. The tool not only displays the allocation from the incumbent solution to the user, it also allows the user to interfere with the solution process by fixing, prohibiting, and shuffling the assignments by means

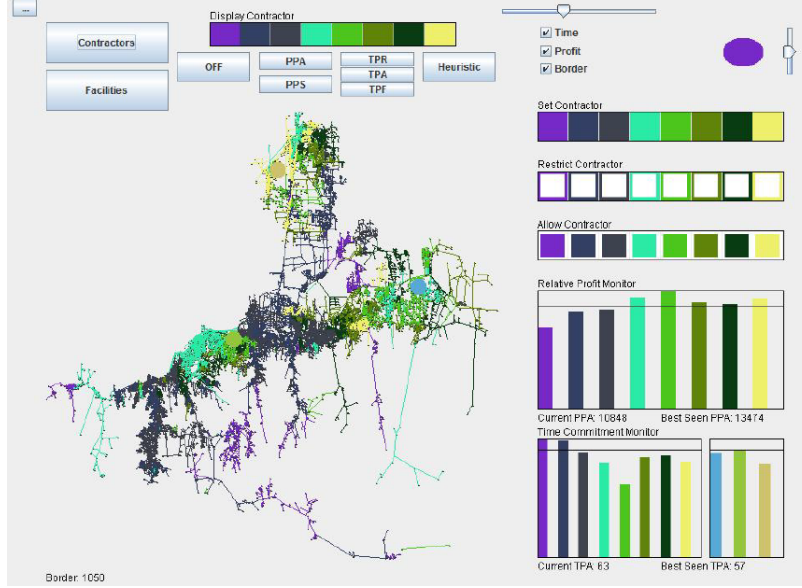


Figure 7: A screenshot of the decision support tool by Stilp et al. [116]

of separate buttons. Each action modifies the model throughout the process, and the user is free to interrupt the run and obtain the best solution once a satisfactory allocation is achieved.

3.3 Infrastructure Restoration

In the aftermath of a large scale disruption, infrastructure restoration problems consider the repair processes on power, telecommunication, and water networks so that (i) the beneficiaries restart receiving the services, and (ii) pre-event flows can be re-established as quickly as possible. The main reason transportation network restoration and other infrastructure restoration problems are treated as separate classes in our review is that for the former, disruption in the transportation network and the resulting loss of connectivity also hamper the transportation of repair crews and vehicles, whereas for the latter all parts of the network are accessible at any time for repair.

As also given in Table 8, the main decisions in infrastructure restoration problems consist of the allocation of repair resources to damaged parts of the network, scheduling of the repairs, location of temporary facilities to provide spare capacity to account for the loss of flow in other parts of the network, installation of nodes and arcs to increase the level of connectivity of the network, and decisions of how flows should be directed once repair is underway and the service is (at least partially) restored.

The problem of workforce assignment, scheduling of repairs, and flow decisions has been considered in many variants and solved in a variety of ways. Exact approaches (Guha et al. [55], Chien

[32], Gong et al. [53], and [37]) consider only a subset of these decisions, whereas heuristic and metaheuristic approaches (mainly genetic algorithms and simulated annealing) are used when all such decisions are considered, as in Sato and Ichii [62], Fiedrich et al. [97], Hegazy et al. [65], Lee and Kim [67], Wang et al. [52], and Furuta et al. [69].

Infrastructure restoration models are also developed in the pre-event stage, considering the uncertainties in the nature of the disruption and the demands of the beneficiaries. Xu et al. [68] and Coffrin et al. [54] formulate stochastic programming models to incorporate uncertainties into the modeling process, whereas Çağnan et al. [98] and Çağnan and Davidson [99] develop discrete event simulation models and assess the performances of various repair scheduling schemes.

One way to overcome the loss of capacity in a disrupted power system is the installation of temporary facilities or new nodes or arcs into the network. Balakrishnan et al. [31, 92] consider the problem of where to install such facilities (which could be of different types and capacities) to provide spare capacity for the network. With a single type of facility, instances of reasonable size can be solved exactly (by means of cutting planes and branch-and-bound); whereas the case with multiple facility types requires the use of heuristics and approximation methods. The addition of new nodes and arcs to increase the connectivity of the network is considered in Nurre et al. [94] and Nurre and Sharkey [96], where the scheduling problem is solved using heuristics based on dispatching rules.

A recent aspect of focus in the study of infrastructure systems is the interdependency among various infrastructure networks. As an example, certain nodes in the telecommunication network (particularly those that distribute the calls) require power to operate, which in turn is supplied by the power distribution network [95]. Hence, the restoration of these two networks should take into consideration the interdependency of services as well. Studies on interdependent network restoration include Lee et al. [33, 34], where an exact solution approach and a user interface are presented; Cavdaroglu et al. [95], where addition of extra arcs is also considered, Sharkey et al. [45], where restoration operations also have an interdependent nature, and Gonzalez et al. [100], where a hybrid simulation and optimization approach is proposed.

Given the wide variety of application areas and decisions, infrastructure restoration problems may also involve a wide variety of objectives as well. A unique objective for this stream is the *delay* or *latency* of services, which refer to the time until the beneficiaries restart receiving the full service after the disruption. As given in Table 5, other objectives in this area include the total time/distance incurred by the repair teams, makespan of restoration operations, utility or benefit

from providing the service to the beneficiaries through the restored network, total cost of operations and the resulting flow, and the total flow throughout and at the end of the restoration process.

3.4 Network Construction

Network construction and expansion problems have received a vast amount of attention in the network optimization literature. In this review, we focus on those that either directly relate to network construction in preparation for or in the aftermath of large-scale catastrophic events, or those that can be directly implemented in such cases, although no mention of humanitarian operations or disasters is made in the corresponding work.

Table 9 shows that the main decisions in network construction problems are the selection of which potential network components to construct or upgrade, sequencing of the arc or node construction decisions, location of facilities in the constructed network, and the flow of commodities or people following the construction.

An important aspect regarding network construction decisions is the equity of services provided after the construction is complete. Depending on the context, equity has been modeled in a number of different ways. Meng and Yang [16] stipulate that the ratio of travel cost before and after the road enhancement is complete to be within a certain threshold for all users. In Antunes et al. [26], the objective is to minimize the number of points where aggregate weighted accessibility measure is smaller. Feng and Wu [19] minimize the differences between accessibility measures of users between regions and within each region. Chen and Yang [18] define an equity measure similar to Meng and Yang [16], and enforce the ratio of the travel time before and after the improvement to be within a certain threshold between each origin-destination pair. Similarly, Campbell and Lowe [24] aim to minimize the maximum-length shortest path between any pair of nodes. While not specifically focusing on equity, other studies that consider accessibility measures include Murawski and Church [35], Peeta et al. [60], Santos et al. [73], and Maya-Duque et al. [84].

One way to model the cases where network construction/improvement and flow of people are considered is the use of bilevel programming, where the network construction is handled in the upper model, whereas the lower model considers the flow decisions. Examples of bilevel models in network construction include Meng and Yang [16], Gao et al. [50], Kim et al. [70], and Feng and Zhang [22]. where the solution methods are simulated annealing, exact mixed integer programming, simulated annealing, and genetic algorithms, respectively.

A number of studies in network construction specifically consider the addition of arcs to a

Table 9: Main decisions in network construction

References	Decisions			
	Selection of components to construct/upgrade	Flow of commodities/people	Facility location	Sequencing of arc/node construction
Krumke et al. [30], Antunes et al. [26], Feng and Wu [19], Scaparra and Church [79]	X			
Meng and Yang [16], Chen and Yang [18], Gao et al. [50], Campbell and Lowe [24], Kim et al. [70], Murawski and Church [35], Ukkusuri and Patil [59], Peeta et al. [60], Santos et al. [73], Maya-Duque et al. [84], Feng and Zhang [22], Baxter et al. [42], Engel et al. [102]	X	X		
Pourn Mohammadi [103]			X	X
Averbakh [39], Averbakh and Pereira [25, 101], Kalinowski et al. [46]				X

Table 10: Main decisions in road restoration/rehabilitation/inspection

References	Decisions					Temporary depot location
	Restoration/inspection schedule	Selection of roads to restore	Routing of crews	Flow of commodities/people	Project prioritization	
Tamura et al. [61], Kiyota et al. [56], Cho et al. [113], Aksu and Özdamar [104], Alvarez et al. [44], Ye and Ukkusuri [48]	X					
Chen and Tzeng [63], Chen and Zheng [64], Bonyuet et al. [105], Wang and Hu [51, 52], Maya-Duque and Sörensen [80], Wang and Chang [77], Yan et al. [86], Ransikarbun and Mason [27]		X		X		
Feng and Wang [112], Lagaros and Karlaftis [20], Kallioras et al. [21], Maya-Duque et al. [57], Akbari and Salman [49]		X	X			
Karlaftis et al. [66], Orabi et al. [71, 72]		X			X	
Yan and Shih [23, 106], Chen et al. [74], Yan et al. [107, 108]			X	X		
Liberatore et al. [17]				X		
Torabi et al. [41]	X		X			X
Asaly and Salman [43]		X	X	X		

disrupted network so that all nodes become connected. Averbakh [39] develops polynomial-time algorithms for makespan minimization on a network where all demand nodes are on a line. Averbakh and Pereira [101] present complexity results, develop a mixed integer programming model, and propose a branch-and-bound solution approach for the more general case. Averbakh and Pereira [25] consider the same problem with tardiness objectives and develop heuristic approaches. In Baxter et al. [42], arc opening and flow decisions are made so that arc opening costs and penalty due to unsatisfied demand are minimized. Kalinowski et al. [46] focuses on maximizing the total flow over multiple periods and develops exact, approximation, and heuristic approaches, whereas Engel et al. [102] propose approximation models for a generic minimization function.

3.5 Road Restoration and Rehabilitation

Transportation infrastructure restoration and rehabilitation problems differ from those that consider other infrastructure networks in that disruptions in road networks generally lead to loss of physical connection with certain parts of the network. Hence, at any given time, only a subset of the roads can be restored or repaired. Given the wide range of practical applications, road restoration and rehabilitation problems are well-studied in the network restoration and recovery literature.

Table 10 presents the set of decisions addressed in road restoration and rehabilitation problems. Similar to the restoration of other infrastructure networks, the decisions of restoration scheduling, road selection for restoration, repair crew routing, and the subsequent flow of commodities or people after restoration is complete are also inherent in road network restoration as well. Additional higher level decisions of which restoration projects to select among alternatives and locations of temporary depots may also be of consideration.

Regarding restoration scheduling, Kiyota et al. [56] develop a dynamic programming approach to maximize total utility over time, whereas in Cho et al. [113], the focus is on minimizing total costs due to structural losses and repair. More recent studies in this area use timeliness of operations as the main objective. Aksu and Özdamar [104] develop an exact approach to minimize the weighted sum of restoration times, and Alvarez et al. [44] propose an exact solution approach to minimize total delivery time. In Ye and Ukkusuri [48], the main objective is to maximize the sum of recovery ratios of system performance during reconstruction, and an exact approach is developed.

The decision of which roads or bridges to restore is generally accompanied by flow decisions in the literature. Among these studies, Bonyuet et al. [105] develop heuristics to minimize total travel cost, Karlaftis et al. [66] devise a genetic algorithm to allocate funds to bridge repair so that

Table 11: Main decisions in snow removal

References	Decisions	
	Assignment of vehicle to roads	Vehicle routing
Handa et al. [81, 82]		X
Haghani and Qiao [109], Perrier et al. [110], Fu et al. [36], Jang et al. [111], Salazar-Aguilar et al. [83], Xie et al. [75], Quirion-Blais et al. [85]	X	X

expected condition improvement is maximized, Maya-Duque and Sörensen use GRASP and VNS to minimize the total time to the nearest regional center, and Ransikarbum and Mason propose an exact approach to minimize the equity-based objective of minimizing the maximum proportion of unsatisfied demand.

A number of studies in this stream make use of time-space networks to determine arc selection for repair, routing of repair vehicles, and flow decisions. In Yan and Shih [106], the objectives of makespan for repair and relief distribution are separately treated, and a heuristic that uses a weighted version of these objectives. Yan et al. [107] develop heuristics for the case with multiple arc types and aim to minimize short-term operating costs. In Yan and Shih [23] and Yan et al. [86], ant colony optimization approach is used to minimize the makespan for repair, whereas Yan et al. [108] consider stochastic travel times and use heuristics to minimize short-term operating costs.

As mentioned, routing of repair vehicles in road restoration is exacerbated by the issue of disconnected arcs in the disrupted network. Routing studies in this area include Chen et al. [74], Lagaros and Karlaftis [20], Kallioras et al. [21], Asaly and Salman [43], Liberatore et al. [17], Akbari and Salman [49], and Maya-Duque et al. [57]. The most widely used objective in these studies is timely connection of demand nodes to the connected portion of the network so that relief demand can be satisfied.

Bilevel models are used in road recovery studies when repair and flow decisions are made by separate stakeholders. In Chen and Tzeng [63] and Chen and Zhen [64], upper and lower level decisions consist of damage point reconstruction and flow of traffic, respectively. Wang and Hu [51] focus on the fraction of capacity recovered, whereas Wang and Chang [77] decide on the number of damaged lanes to be repaired in the upper level.

3.6 Snow Removal

As described by Minsk [117], large-scale snow removal poses unique challenges, which may not be faced during debris removal or infrastructure repair. These include (1) partial area coverage,

where some segments may be traversed, but do not need to be serviced, (2) service hierarchy, where important segments should be serviced first, (3) workload balance, where plowing work needs to be evenly distributed among vehicles, (4) street-vehicle dependence, where smaller streets may require smaller vehicles, (5) turn restrictions, as left-turns leave snow windrow in the middle and U-turns leave snow in the intersection, and (6) recurring service, where higher snow amounts may require multiple times of service.

A survey of prior models and solution approaches in snow removal is made by Perrier et al. [118, 119, 120, 121]. Table 11 matches the papers in this field with the main decisions in snow removal. Here, all studies include the decisions of vehicle routing with a subset of the constraints described above. Typical objectives include total tour length or cost, overall makespan, makespan for different road classes, and total cost of service. The inherent difficulty of the resulting routing problems has led to only one study applying an exact approach (Fu et al. [36]). Other studies resort to heuristics (Haghani and Qiao [109], Perrier et al. [110], and Jang et al. [111]) and metaheuristics such as memetic algorithms (Handa et al. [81, 82]), genetic algorithms (Xie et al. [75]), and adaptive large-scale neighborhood search (Salazar-Aguilar et al. [83] and Quirion-Blais et al. [85]).

4 Conclusions and Potential Research Directions

This paper has presented a comprehensive review of the recent papers on network restoration and recovery within the context of humanitarian operations. A total of 100 papers were reviewed, 79 of which are unique to this study and are not included in any of the review papers in the fields of disaster management and humanitarian operations. This uniqueness is mainly due to a more extensive search in other fields such as electrical and civil engineering, and to the fact that studies that are seemingly outside the field of humanitarian applications provide useful insights.

By classifying the studies in terms of problem areas, main decisions, objectives, and solution methods, this paper not only serves as a guideline for researchers and practitioners that are not familiar with this area, but it also aims to help researchers in the field of humanitarian operations and network optimization to detect research gaps in this body of literature.

A number of potential research directions can be drawn from the results of this review. First, as noted by Faturechi and Miller-Hooks [14], a vast majority of the studies regarding transportation infrastructure performance in disasters focus on only one stage of the disaster life cycle. This fact

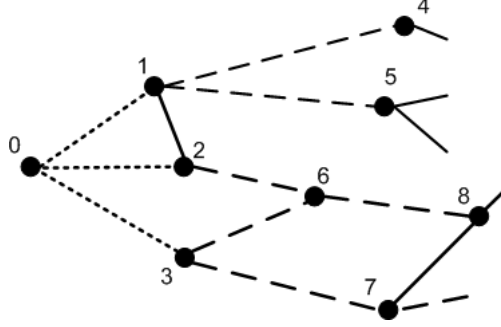


Figure 8: A partial network for the stochastic debris clearance problem, where clearance starts from node 0 (Çelik et al. [58]). Dashed edges are debris-covered, whereas solid edges represent traversable edges

holds for the papers in this study as well. As pre- and post-disaster decisions are interdependent, it is of significant practical use to consider post-disaster network restoration and recovery when planning for pre-disaster decisions. An example for this is the inventory prepositioning problem, where the pre-disaster decisions of facility location and inventory prepositioning may be affected by the post-disaster vulnerability and repair of the network, since these also affect the relief transportation decisions. To the best of our knowledge, the only study in the literature that makes such a consideration is by Wisetjindawat et al. [122], where post-disaster repair decisions are taken as inputs to the model. In an ongoing work, Aslan and Çelik [123] also consider road repair as part of the decisions, formulate a two-stage stochastic program, and propose a heuristic approach based on sample average approximation. It may be of interest to further analyze the effect of post-disaster road or infrastructure repair on other disaster preparedness problems as well.

An important aspect of decision making in humanitarian operations is the inherent nature of uncertainty in the environment. Furthermore, the uncertain features of the system are generally revealed over time. While uncertainty is incorporated into a number of studies reviewed in this paper, most studies consider a two-stage setting, where all uncertainty is revealed at a certain point in time. In stochastic network restoration problems such as debris clearance and road repair, uncertainty on the demand or resource requirements for repair/clearance may be revealed in a number of ways. Figure 8 illustrates such a situation for the debris clearance problem where debris amounts are uncertain and dashed edges are debris-covered [58]. Assuming that clearance starts from node 0, the decision maker has exact information about the debris amounts on edges $(0,1)$, $(0,2)$, and $(0,3)$, whereas only probabilistic information is available on the debris amounts of the remaining debris-covered edges. Upon clearing edge $(0,1)$, exact amount information becomes available for

edges (1,4), (1,5), and (2,6), which have become reachable. Such information update mechanisms can be incorporated into multiple-period stochastic approaches, such as partially observable Markov decision processes.

Another information update mechanism in the aftermath of a large-scale disaster is the use of remote updates, where the need to reach the source of uncertainty by the repair/clearance crew is eliminated. Such an approach is carried out in an ongoing work by Farajkhah and Çelik [124], where unmanned air vehicles (UAVs) are used for information collection after the disaster to aid in the debris clearance efforts. Before the disaster, a set of UAV base locations are determined, along with a set of routes that the UAVs should follow after the disaster. In the aftermath, the predetermined routes are followed and based on the debris amount information received from the UAVs, a clearance sequence is determined, which further establishes connectivity and flow of relief supplies between supply and demand nodes. The authors use a two-stage stochastic programming model and heuristic approaches to solve this problem in reasonable time.

With the increase in the number of disasters and long-term humanitarian issues, the number and variety of problems related network restoration, and hence the amount of research on this topic is also expected to increase. This requires that the researchers working in this area be aware of prior work over different problem types and across disciplines, for which this paper aims to serve as a starting point. While the review presented here is almost extensive for the last decade and a half, researchers should also be alert on new developments for seemingly unrelated problems and methods (particularly in network optimization) that can be applied directly or with minor modifications on network restoration problems in humanitarian operations.

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